Paper 110

Proceedings of the Eighth International Conference
on Engineering Computational Technology,
B.H.V. Topping, (Editor),
Civil-Comp Press, Stirlingshire, Scotland

Simulation of the Long-Term Behaviour of an Underground Structure in Rock Salt

A. Pudewills
Karlsruhe Institute of Technology
Institute for Nuclear Waste Disposal, (KIT-INE)
Eggenstein-Leopoldshafen, Germany

Abstract

This paper summarizes the current state of numerical simulations of long-term geo-mechanical behaviour of an existing salt mine. Within the frame of a national joint project, five participants performed benchmark like calculations on a 3D underground structure. The main objective of the project was to evaluate the ability of the different models to correctly describe the relevant deformation phenomena in rock salt under various influences. In the first step of the benchmark calculations, the initial state of stress taking into account the creep behaviour of the rock salt and an intercalating clay layer has been determined. After excavation of the main room and different drifts the calculations have been continued over 100 years. Finally, the numerical results and in situ measurements are compared.

Keywords: constitutive model, finite element modelling, rock salt, underground structures.

1 Introduction

In recent decades, a large and detailed experimental and theoretical knowledge base for the geo-mechanical behaviour of rock salt has been compiled by several groups [1, 2]. Between 2007 and 2010, the German Federal Ministry of Education and Research has funded a joint project within its research program "Improvement of tools for the safety assessment of underground repositories". The five project partners performed 3D benchmark calculations of an old underground structure in rock salt of the Angersdorf mine in northern Germany [3]. The aim of the project was to evaluate the ability of the models to correctly describe the relevant deformation phenomena in rock salt under various influences, (i.e. transient and steady-state creep, the evolution of dilatancy and damage, short-term failure and long-term creep failure, post-failure behaviour and residual strength) and to increase confidence in the results of numerical simulations and enhance the acceptance of the results.

In our institute the finite element (FE) code ADINA was used to study the mechanical behaviour of rock salt [4]. A new viscoplastic constitutive model for rock salt that can describe the volumetric strain (dilatancy) and the damage of the rock has been proposed and implemented in this code [5]. The model parameters for the numerical simulation have been evaluated on the available laboratory experiments [3, 6]. The Angersdorf salt mine consists of a regular pattern of large rooms and pillars at a depth of about 530 m. Therefore, a 3D vertical section was chosen as a representative model. The benchmark results and the comparison of several results with in situ measurements have shown that the numerical model is able to describe the main behaviour of the rock salt such as transient and steady-state creep, dilatancy and material damage around underground openings. A comparison of calculation results from five project partners was performed in a separate synthesis report [1] and a number of papers [2, 7].

2 Modelling approach

Within the frame of the joint project, each partner has to perform 3D simulations of a real underground structure in rock salt. The Angersdorf mine situated near the town of Halle was selected because this mine has a simple regular structure of rooms and pillars and there are a large amount of in situ and laboratory measurements data available.

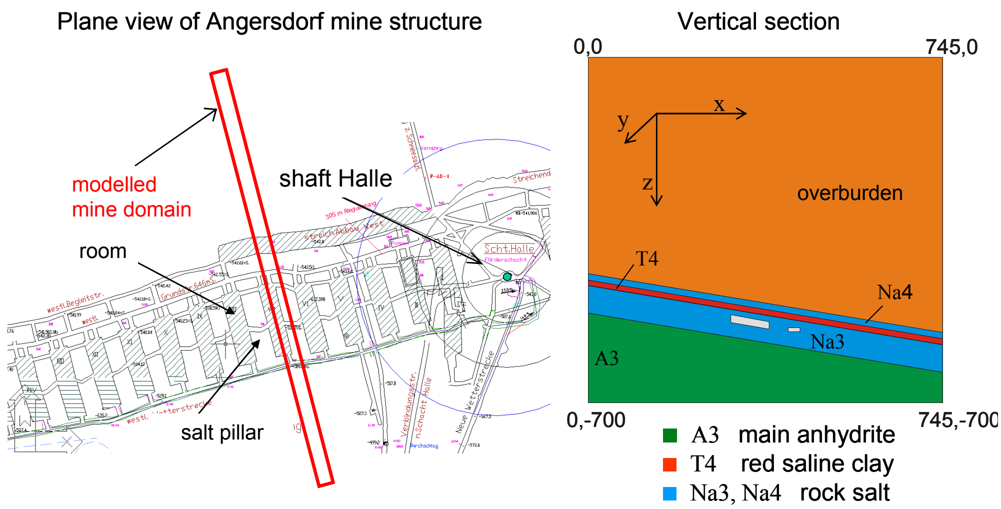

Figure 1: Horizontal plane view of the room and pillar geometry of the Angersdorf mine. The position of the modelled domain is marked in red. The geological map of the modelled area is show at the right.

2.1 Angersdorf salt mine

The Angersdorf mine is a part of the mine complex Teutchenthal where carnallite and rock salt was excavated from 1908 until 1982. Figure 1 illustrates a view of the mine structure with large rooms and pillars. This figure presents also a vertical cross-section through the geological structure at the location of the model. The geological details of the formation is described in Ref. [3] and is composed of five rock layers with an inclination of 9º in the north direction.

Measurements of the surface subsidence above the mine are available from the beginning of the underground excavation and are used for comparisons with the simulation results. Laboratory test data on rock salt and additional material for further analysis were also available and the mine is still accessible for further in-situ measurements.

2.2 Definition of the finite element model

Considering the regular pattern of large rooms and salt pillars at a depth of about 530 m a 3D vertical slim section representing a half of a main room and a half of the salt pillar was chosen as a representative calculation model. The total dimension of the numerical model in direction of x/y/z was 745m/20m/800 m.

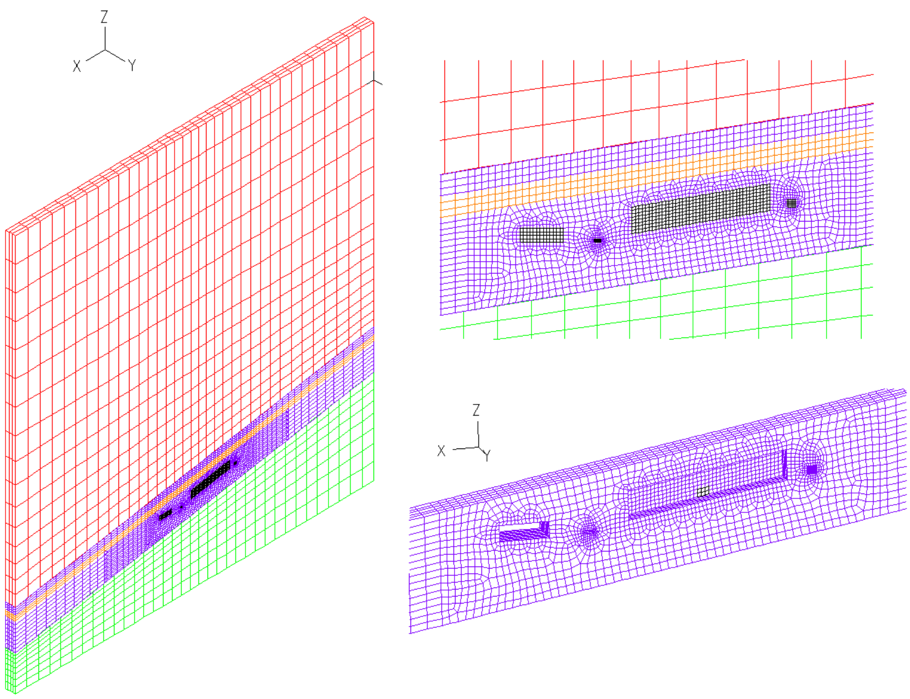

Figure 2: FE-model of the Angersdorf mine section as indicated in Figure 1. The rock layers and the main room are inclined by 9° to the north. At the right: Detail of the model with the underground openings before and after excavation.

The FE model consists of about 86000 elements with 20 and 8 nodes.

3 Constitutive models and material parameters

3.1 Rock salt

The constitutive model for rock salt proposed in this project is based on the assumption that the total strain rate is split into elastic and viscoplatic parts as follows:

$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{vp} \tag{1}$$

$\dot{\varepsilon}_{el}$: elastic strain rate

$\dot{\varepsilon}_{vp}$: viscoplastic strain rate

The elastic behaviour is assumed to be time-independent. Furthermore, the viscoplastic strain rate is decomposed into a viscoplastic strain rate by constant volume and a viscoplastic strain rate due to damage that considers the volume change, such as dilatancy or compaction of the material:

$$\dot{\varepsilon}_{vp} = \dot{\varepsilon}^{c}_{vp} + \dot{\varepsilon}^{d}_{vp} \tag{2}$$

$\dot{\varepsilon}^{c}_{vp}$: viscoplastic strain rate without volume change

$\dot{\varepsilon}^{d}_{vp}$: viscoplastic strain rate due to damage which describes a volumetric strain

For each viscoplastic strain rates, an associated flow rule is used:

$$\dot{\varepsilon}_{vp} = \gamma < \Phi\ (F(\sigma)) > \partial F / \partial \sigma \tag{3}$$

where $\gamma = a_1 \exp(-a_2 / T)$ is the fluidity parameter; a_1 and a_2 are material constants and T is the temperature. The term $\Phi\ (F)$ denotes a monotonic function of the yield function (F). The meaning of the brackets $< >$ is as follows:

$$\begin{aligned} < \Phi\ (F) > &= 0 && \text{if } F \leq 0 \\ < \Phi\ (F) > &= \Phi\ (F) && \text{if } F > 0 \end{aligned} \tag{4}$$

The function $\Phi\ (F)$ is defined as:

$$\Phi\ (F) = (F - F_o)^{\mathrm{m}} \tag{5}$$

where m is an arbitrary constant and F_o is the uniaxial yield stress and set to zero in this paper. For our viscoplastic model, the functions F^c and F^d are defined as follows:

$$F^c = q^2 \quad \text{(without volume change)} \tag{6}$$

$$F^d = n_1\, p^2 + n_2\, q^2 \tag{7}$$

where p = the mean stress; and q = standard stress deviator; n_1, n_2 are material functions of the volumetric strain, ε_{vol} ; and expressed as:

$$n_1 = c_1 \left(q^2/p^2 - c_2 \left(\eta_0 + \varepsilon_{vol}\right)/\left(1 + \varepsilon_{vol}\right)\right) \tag{8}$$

$$n_2 = 1 - c_3 \cdot n_1 \, p^2/ q^2 \tag{9}$$

with c_1, c_2, and c_3 being material constants to be determined by laboratory tests. In the present approach η_0 is the initial porosity of the undamaged rock salt and $\varepsilon_{vol} = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$

This viscoplastic material model for damage is based on the mathematical formulation proposed by Hein [8] for granular materials, such as crushed salt, and was implemented in the finite-element code ADINA [9]. Separate criteria for shear and tensile fracture and a compression-dilation boundary [10], [11] are available to judge the damage of rock salt (i.e. micro-cracks or fractures):

- *Shear stress criterion for compression*

$$\tau_f \geq 2.612 \, |\sigma_m|^{0.78} \tag{10}$$

where τ_f = predicted shear stress at failure; σ_m = mean stress

- *Tension-induced failure* is assumed if the max. principal stress exceeds a tension of 2 MPa.

- *Compression-dilation boundary*

$$\tau_{cd} \;\geq\; 0.899\sigma_m - 0.0167 f_2 \, \sigma_m^2 \tag{11}$$

Recently, a permeability model for damaged rock salt has been proposed by [12], it is presented below. This model represents a relation between the mean stress and dilatant volumetric strain (i.e. rock porosity):

$$k = \frac{k_{tp}}{\left(\dfrac{\varepsilon_{vol}}{\phi_{tp}}\right)^{-p_1} + \left(\dfrac{\varepsilon_{vol}}{\phi_{tp}}\right)^{-p_2}} \tag{12}$$

with $k_{tp} = a_k \cdot exp\left(-p_c \cdot b_k\right)$

$\phi_{tp} = a_\phi \cdot \exp\left(-p_c \cdot b_\phi\right)$

The material fitting parameters which are based on previous simulations [5] are listed in Table 1.

Properties	*Parameters*
Thermo-elastic properties	$E = 25\ GPa;\ \nu = 0.25;\ \alpha = 4.2E\text{-}05\ 1/K$
Transient creep	$a_0 = 0.018;\ a_1 = 240;\ a_2 = 0.112;$ $Qc/R = 6495\ K^{-1}$
Viscoplastic damage	$m = 2.25;\ c_1 = 0.3;\ c_2 = 400;$ $c_3 = 2;\ \eta_0 = 0.02\%$
Hydraulic properties Equation (12)	$p_1 = 4;\ p_2 = 1;\ a_k = 4.27E\text{-}14;$ $b_k = 1.26;\ a_\Phi = 0.0263;\ b_\Phi = 0.3093$

Table 1: Main properties of rock salt (Na3 layer) and the parameters used for the numerical simulations with the ADINA code

3.2 Behaviour of other rock layers

The material models and the parameters of the different geological layers are given in Table 2. These models and the fitting parameters based on rock-mechanics laboratory tests [3, 13] are used by all benchmark participants.

			ρ	**E**	**ν**	**c**	**φ**	**σ_z**	**A**	**n**
Material		**Model**	[t/m^3]	[GPa]	[-]	[MPa]	[º]	[MPa]	[d^{-1}]	
overburden rock		MC [(1]	2.60	6.0	0.33	0.5	30	0		
red saline clay	T4	Creep	2.30	10.2	0.27				1.6E-06	1
anhydrite	A3	Elastic	2.90	60.0	0.25					
rock salt	Na3, Na4		2.15	25.0	0.25					

[(1] MC is the abbreviation of Mohr-Coulomb model

Table 2: The material models and the parameters for different rock layers used for the numerical simulations

4 Results of three-dimensional calculations

In the joint project, each partner performed three-dimensional simulations of the real underground structure in rock salt. Taking into consideration the constitutive relations described in the preview sections and the elastic parameters from the Tables 1 and 2 the initial state of lithostatic stress was simulated firstly. After about

10000 years an equilibrium stress field between the creeping rocks and the elastic rocks was calculated. Then the excavation of all rooms and drifts was simulated instantaneously and the calculation was continued over further 100 years. The simulation results will be presented as time histories at different positions around the large opening and as distribution along representative cross sections at times t = 50 years (the actual situation) and t = 100 years (as a prognosis).

4.1 Displacements

The subsidence of the earth surface induced by mining activities was measured at different observation points over 50 years. A comparison of this data with the calculation results was used to adjust the value of the steady state creep parameters in the numerical modelling. In Figure 4 the development of the calculated vertical and horizontal displacements at different positions around the excavations and also the calculated subsidence of the point (**a**) at the model upper surface are presented. Figure 5 shows the distribution of displacement in a vertical section through the mid-plane of the 3D model about 100 years after excavation of the main room and drifts. The results illustrate the high convergence of salt near the drift which is in concordance with the in situ observations. More details are given in refs. [2, 7]

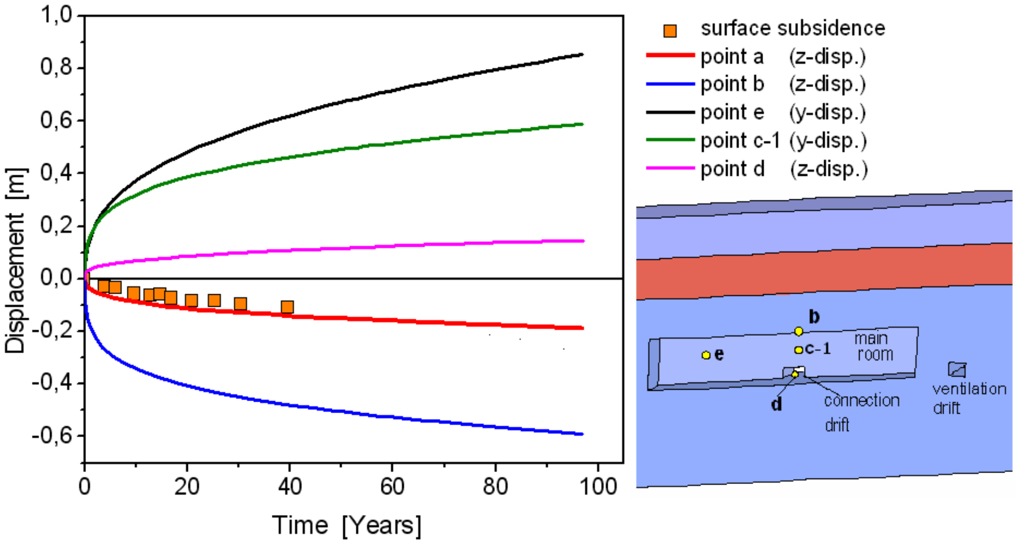

Figure 4: Development of vertical and horizontal displacements at different positions in the main room. Point (**a**) is located at the model upper surface.

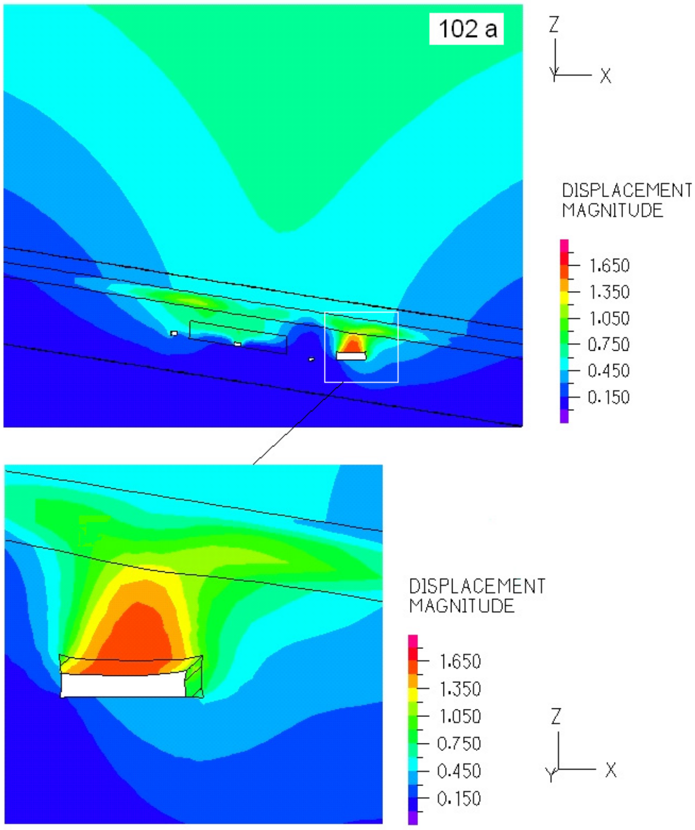

Figure 5: Distribution of displacement 102 years after excavation of all openings.

4.2 Strains and Stresses

From all the calculations only same illustrative results of ADINA code simulation will be presented. The development of normal stresses along the proposed vertical cross-section α-1 is drawn in Figure 6 and a comparison of the calculated minimum principal stress with in situ measurements (hydro-frac tests) in a borehole through the pillar is shown in Figure 7. Figure 8 shows the distribution of the effective creep strain near the excavations at the time point t = 50 years. The calculated dilatancy (porosity) of rock salt around the small connecting gallery is shown in Figure 9 together with a photograph of a real drift at the same location in the salt mine. In Figure 10 the calculated porosities inside the modelled pillar were compared with the in-situ data of the rock salt. The estimated in situ permeability and the simulation results 50 years after excavations show a satisfactory agreement. Further calculation results over 100 years provide the prediction of the expected values.

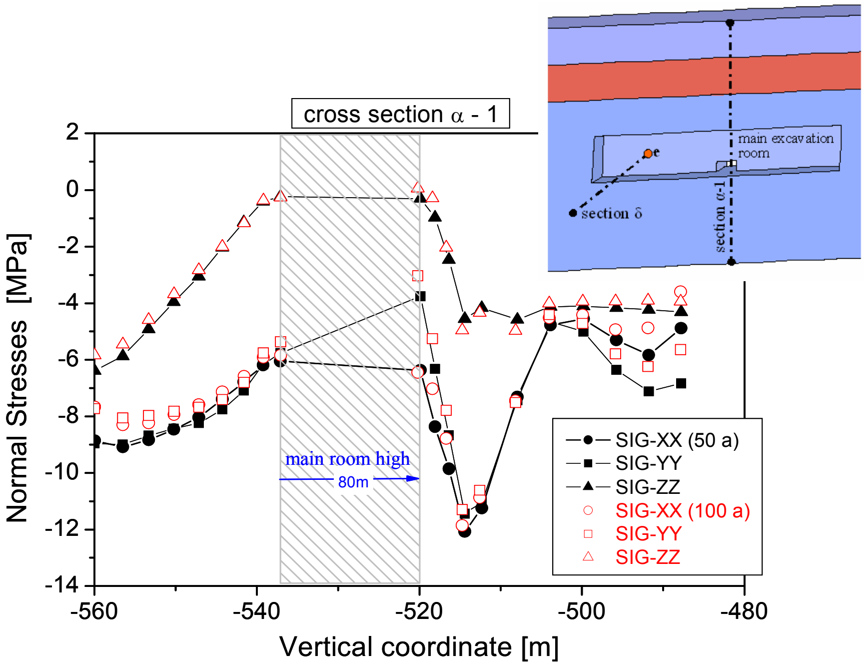

Figure 6: Distribution of the normal stresses along a vertical section (α-1) at the mid plane of the main room.

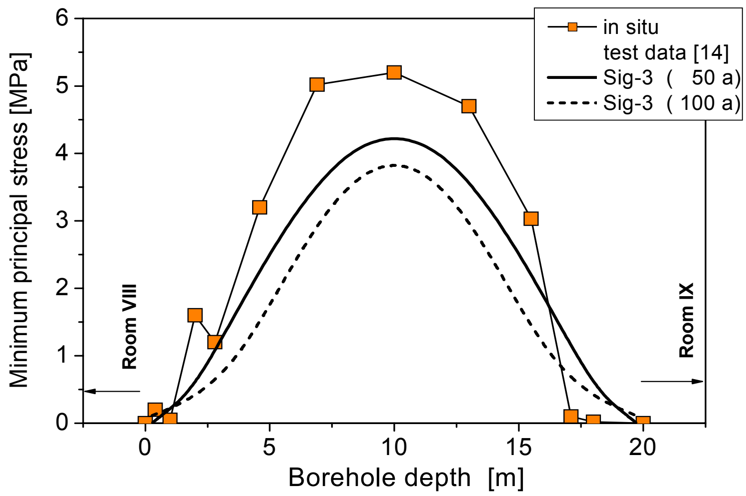

Figure 7: Distribution of calculated and measured minimum principal stress in the pillar between two large excavation rooms (section δ).

5 Conclusions

The benchmark calculations and comparisons of the results in the frame of the project have yielded the following results:

- The predictive capabilities of the constitutive model for rock salt (developed originally for crushed salt) have been improved to describe the rock dilatant deformations. This model is able to simulate the main behaviour of the rock salt such as transient and steady state creep, dilatancy and material damage.
- The 3-D modelling of the complex section of the Angersdorf mine was an important test of the numerical tools used for the benchmark calculations.
- In addition, the work revealed the necessity of further development and improvement of the constitutive model for rock salt in order to describe the post failure behaviour and the influence of the elevated temperature.

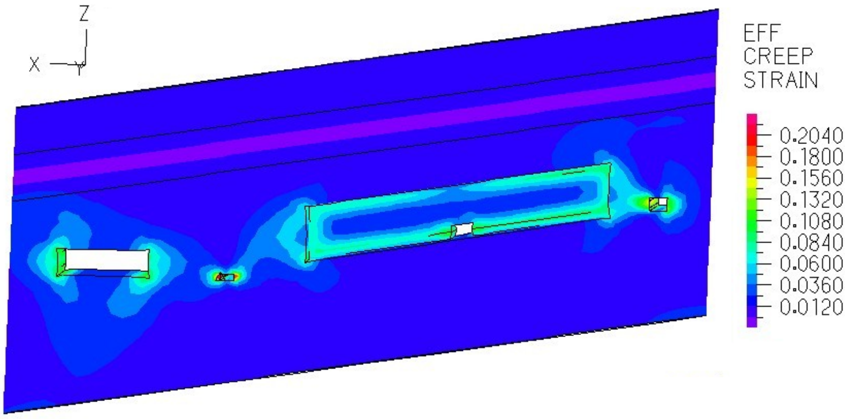

Figure 8: Distribution of calculated effective creep strain in the rock salt around the excavations (t = 50 years)

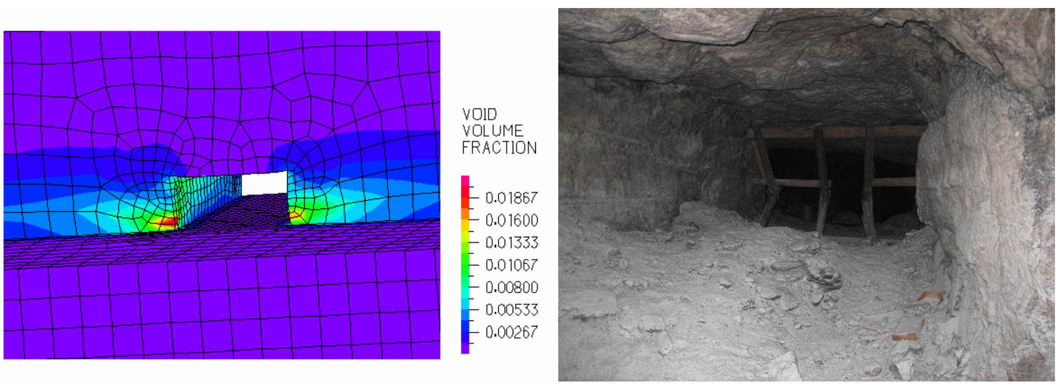

Figure 9: Volumetric strain (porosity) around the connecting drift between room VIII and room IX at t = 50 years and a photograph of such drift [14].

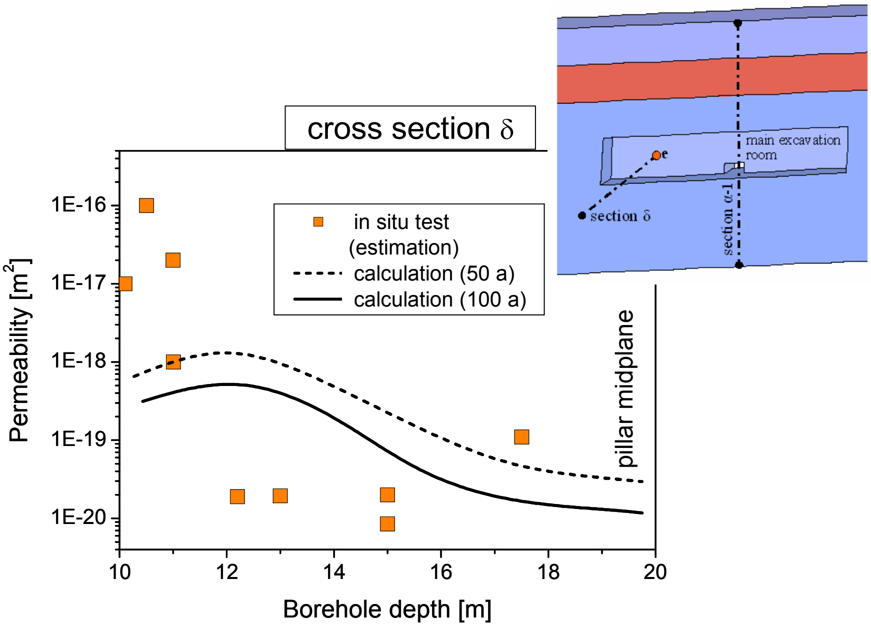

Figure 10: Distribution of calculated and estimated permeability of rock salt in the pillar between room VIII and IX (ref. [14]).

Acknowledgements

Financial support of the German Federal Ministry of Education and Research (BMBF) and the advisory support by the Project Management Agency Karlsruhe (PTKA-WTE) in the project is gratefully acknowledged.

References

[1] A. Hampel, O. Schulze, U. Heemann, F. Zetsche, R.-M. Günther, K. Salzer, W. Minkley, Z. Hou, R. Wolters, U. Düsterloh, D. Zapf, R. Rokahr, A. Pudewills, "Die Modellierung des mechanischen Verhaltens von Steinsalz: Vergleich aktueller Stoffgesetze und Vorgehensweisen", Abschlussbericht (Synthesebericht + Einzelberichte zum BMBF-Verbundprojekt (FKZ 02C1004-1054), Projektträger Karlsruhe, Wassertechnologie und Entsorgung (PTKA-WTE), Karlsruher Institut für Technologie (KIT), 2007.

[2] A. Hampel, R.-M. Günther, K. Salzer, R.-M. Günther, W. Minkley, A. Pudewills, B. Leuger, D. Zapf, K. Staudtmeister, R. Rokahr, K. Herchen, R. Wolters, K.-H. Lux, O. Schulze, U. Heemann, U. Hunsche, "Bencharking of Geomechanical Constitutive Models for Rock Salt", Proc. 44th US Rock Mechanics Symposium (ARMA 2010), Salt Lake City/Utah/USA, 27.-30.06.2010, American Rock Mechanics Association (ARMA), 2010.

[3] IFG, "Langzeitsicherheitsnachweis Grube Teutschenthal, Fortschreibung unter besonderer Berücksichtigung eines Sicherungs- und Verwahrungskonzeptes für das Grubenfeld Angersdorf", Institut für Gebirgsmechanik GmbH, Leipzig, 2006.
[4] Adina R & D Inc., ADINA (Automatic Dynamic Incremental Nonlinear Analysis), Report ARD 01-9, Watertown, MA, US, 2010.
[5] A. Pudewills, "Numerical modelling of the long-term evolution of EDZ: development of material models, implementation in finite-element codes and validation", FZKA-7185, Karlsruhe: Forschungszentrum Karlsruhe, 2005.
[6] O. Schulze, U. Heemann, U. Zetsche, A. Hampel, A. Pudewills, R.-M. Günther, W. Minkley, K. Salzer, Z. Hou, R. Wolters, R. Rokahr, D. Zapf, "Comparison of advanced constitutive models for the mechanical behavior of rock salt - results from a joint research project, I. Modeling of deformation processes and benchmark calculations"' Proc. of the Sixth Conf. on the Mechanical Behavior of Salt (Saltmech 6), Eds.: K. H. Lux, W. Minkley, M. Wallner & H. R. Hardy, Jr., Basic and Applied Salt Mechanics, Hannover, Mai 2007, Taylor & Francis (Balkema), London, p 77-88, 2007.
[7] A. Hampel, K. Salzer, R.-M.Günther, W. Minkley, A. Pudewills, B. Leuger, D. Zapf, R. Rokahr, K. D. Herchen, R. Wolters, U. Düsterloh, "Joint Projects on the Comparison of Constitutive Models for the Mechanical Behavior of Rock Salt - II. Overview of the models and results of 3-D benchmark calculations", Proc. of the 7th Conference on Mechanical Behavior of Salt, Paris, 16-19.04, submitted for publication, 2012.
[8] H. J. Hein, "Ein Stoffgesetz zur Beschreibung des thermomechanischen Verhaltens von Salzgranulat", Dissertation, RWTH Aachen, 1991.
[9] A. Pudewills, M. Krauss, "Implementation of a viscoplastic model for crushed salt in the ADINA programme", Computers and Structures, vol. 72, p 293-299, 1999.
[10] U. Hunsche, "Failure behaviour of rock salt around underground cavities", Proc. of the 7th International Symposium on Salt, Kyoto, 1992. Amsterdam: Elsevier. 1992
[11] N. Cristescu, U. Hunsche, "Time effects in rock mechanics", John Wiley & Sons, 1998.
[12] U. Heemann, S. Heusermann, "Theoretical and Experimental Investigation on Stresses and Permeability in the BAMBUS Project", DisTec 2004, Int. Conf. on Radioactive Waste Disposal, April 26-28, Berlin, 2004.
[13] R.-M. Günther, K. Salzer "A model for rock salt describing transient, stationary, and accelerated creep and dilatancy", Proc. of the Sixth Conf. on the Mechanical Behavior of Salt, Hannover, May 2007, eds. K. L. Lux, W.Minkley, M. Wallner, London: Taylor & Francis (Balkema), p 109-117, 2007.
[14] K. Salzer, R.-M. Günther, W. Minkley, T. Popp, M. Wiedemann, A. Hampel, A. Pudewills, B. Leuger, D. Zapf, R. Rokahr, K. Herchen, R. Wolters, U. Düsterloh, "Joint projects on the comparison of constitutive models – I. Overview of the projects, reference mine for 3-D benchmark calculations, in-

situ measurements and laboratory tests", Proc. of the 7th Conference on Mechanical Behavior of Salt, Paris, 16-19.04.2012, submitted for publication, 2012.